New Bound States of Heavy Quarks at LHC and Tevatron

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Abstract

The present paper is based on the assumption that heavy quarks bound states exist in the Standard Model (SM). Considering New Bound States (NBSs) of top-anti-top quarks (named T-balls) we have shown that: 1) there exists the scalar $1S$–bound state of $6t + 6\bar{t}$ – the bound state of 6 top-quarks with their 6 anti-top-quarks; 2) the forces which bind these top-quarks are very strong and almost completely compensate the mass of the 12 top-anti-top-quarks forming this bound state; 3) such strong forces are produced by the interactions of top-quarks via the virtual exchange of the scalar Higgs bosons having the large value of the top-quark Yukawa coupling constant $g_t \simeq 1$. Theory also predicts the existence of the NBS $6t + 5\bar{t}$, which is a color triplet and a fermion similar to the t'-quark of the fourth generation. We have also considered "b-quark-replaced" NBSs: $n_b b + (6t + 6\bar{t} - n_b t)$ and $n'_b b + (6t + 5\bar{t} - n'_b t)$, etc. We have estimated the masses of the lightest "b-replaced" NBS: $M_{NBS} \simeq (300 - 400)$ GeV, and discussed the larger masses of the NBSs. We have developed a theory of the scalar T-ball's condensate and predicted the existence of three SM phases. The searching for the Higgs boson H and heavy quarks bound states at the Tevatron and LHC is discussed.

1 Introduction: Tevatron and LHC, Higgs boson and T-balls

The Salam-Weinberg theory of Electroweak (EW) interactions describes very well the Standard Model (SM), which is confirmed by all experiments of the world accelerators. This theory predicts the existence of a scalar particle – the Higgs boson. However, this Higgs boson was not observed up to now in spite of the careful searching for this particle. The main problem of the future colliders: LHC, Tevatron, etc. – is just the searching for the Higgs boson H.

The Tevatron collider at Fermilab (Illinois, USA) produces the high energy collisions of proton-antiproton beams. Fermilab has been the site of several important discoveries that have helped to confirm the SM of elementary particle physics. Tevatron experiments observed the first evidence of the bottom quark's existence (in 1977), and completed the quark sector of the SM with the first observation of the top quark (in 1995).

Tevatron has the center-of-mass energy $\sqrt{s} = 1.96$ TeV, and therefore was currently the world's highest energy particle collider.

Large Hadron Collider (LHC) is a new accelerator being built at the European Organization for Nuclear Research (CERN).

The physics motivation provides the guidance for the construction specifications of the LHC machine. At the new frontier of the LHC of the High Energy Physics, the areas that we aim to study with LHC can be summarized as follows.

1.1 Explore the mechanism of the EW symmetry breaking

Although the SM of the EW interactions provides a successful description of particles physics phenomenology (its predictions have been verified by experiments at LEP and Tevatron), the mechanism of the EW symmetry breaking (EWSB) has not yet been tested.

Within the SM, the EWSB is explained by the Higgs mechanism. However, the mass of the Higgs boson m_H is not predicted by theory. Direct searches in the previous experiments (mainly at LEP2) set a low mass limit:

$$m_H \gtrsim 114.4 \quad \text{GeV} \quad \text{at} \quad 95\% \quad \text{CL}.$$

This limit can be indirectly constrained from global fits to high precision EW data which suggest a mass

$$m_H = 89^{+42}_{-30} \quad \text{GeV}.$$

The recent Tevatron result is:

$$115 \lesssim m_H \lesssim 160 \ \ \text{GeV}.$$

If we assume that there is not physics beyond the SM up to a large scale $\Lambda \sim 1$ TeV, then, on theoretical grounds, the upper limit on the Higgs mass can be set to 1 TeV. Therefore,

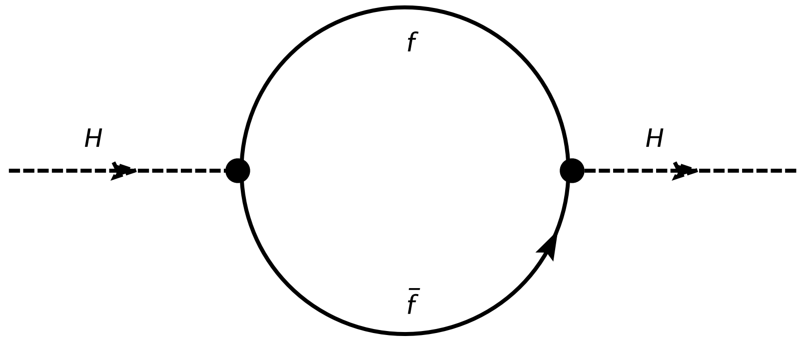

Fig. 1: Fermionic radiative corrections to the scalar Higgs mass (at one-loop level).

there is a need for a machine that can probe the whole mass range, and LHC has been designed for that.

1.2 Physics beyond the SM

There are several arguments, which indicate that the SM is not the final and complete theory. One of these, probably the strongest, is the so-called 'hierarchy problem': if the Higgs particle exists, then the fermionic radiative corrections to its mass will be described (at one-loop level) by the diagram of Fig. 1.

Then the Higgs mass given by theoretical calculations depends on the cut-off Λ for the momentum in loop. Now, if there is not new physics up to the Planck scale, then: $\Lambda \simeq M_{\text{Planck}} \simeq 10^{19}$ GeV, and $m_H(\text{renormalized}) >> (1 \text{ TeV})^2$, unless we fine tune so as to avoid that. Since the last value does not agree with experimental limits, we start to believe that possible new physics exists beyond the SM (for example, SUSY models, etc.).

1.3 EW precision measurements

Because of the high energy and luminosity achieved, the LHC will be a factory of W and Z bosons, as well as of top and bottom quarks.

It is estimated that LHC, during the first year of operation, will give the following events:

$$10^8, \quad W \to e\nu,$$

$$10^7, \quad Z \to e^+e^-,$$

$$10^7, \quad t\bar{t},$$

$$10^{12}, \quad b\bar{b}.$$

LHC will establish the SM parameters. Any observed deviation from the predicted values of the SM observables will be a signal for new physics.

The LHC is currently being constructed in the already existing LEP tunnel of (approximately) 27 km circumference. The machine provides mainly proton-proton collisions. Also it will provide heavy ion collisions as well.

The LHC will produce two counter-rotating proton beams with energy of 7 TeV each. This gives 14 TeV center of mass energy ($\sqrt{s} = 14$ TeV): 7 times bigger than the center of mass energy provided by Tevatron at Fermilab.

The completion of the LHC is expected in the nearest future.

1.4 New bound states of top-anti-top quarks.

We hope that the LHC will provide a solution of the main puzzles of EWSB. The present review, based on Refs. [1-12], is devoted to these problems.

This article is really the outcome of a couple of talks by respectively Holger Bech Nielsen at CERN [1] and Larisa Laperashvili at ITEP seminar [2], which contain a bit more review than usual.

It includes the following three assumptions:

• there exists $1S$-bound state of $6t + 6\bar{t}$, e.g. bound state of 6 quarks of the third generation with their 6 anti-quarks;

• the forces, which bind these top-quarks are so strong that almost completely compensate the mass of the 12 top-quarks forming this bound state;

• such strong forces are produced by the Higgs interactions – the interactions of top-quarks via the virtual exchanges of the scalar Higgs bosons. These forces are determined by the large value of the top-quark Yukawa coupling constant $g_t \sim 1$.

A new (earlier unknown) bound state $6t+6\bar{t}$, which is a color singlet, that is, 'white state', was first suggested in Ref. [3] by Froggatt and Nielsen and now is named T-ball, or T-fireball.

• Theory also predicts the existence of a new bound state $6t+5\bar{t}$, which is a fermion similar to the quark of the fourth generation having quantum numbers of t-quark.

The properties of T-balls are intimately related with the problem of the Higgs boson observation.

2 Higgs and gluon interactions of quarks

If the Higgs particle exists, then we have the virtual exchanges by the Higgs bosons between quarks qq, quarks and anti-quarks $q\bar{q}$, and also between anti-quarks $\bar{q}\bar{q}$ (see Fig. 2), which cause only attraction between all combinations of top and anti-top quarks.

It is well-known that the bound state $t\bar{t}$ – so called 'toponium' – is obligatory of the gluon virtual exchanges (see Fig. 3).

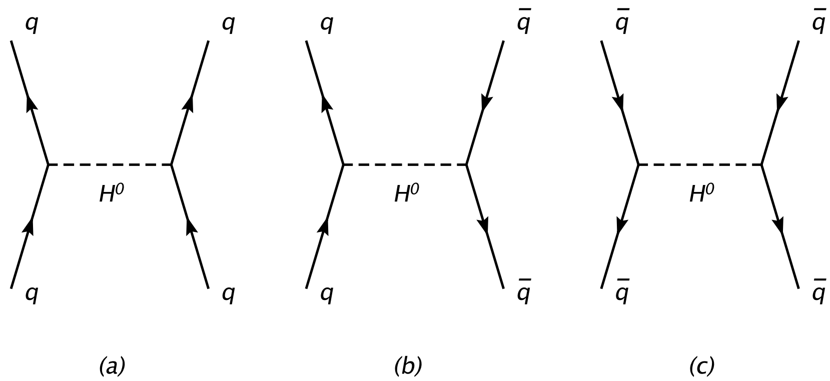

Fig. 2: The virtual exchanges by the Higgs bosons between quarks qq, quarks and anti-quarks $q\bar{q}$, and also between anti-quarks $\bar{q}\bar{q}$.

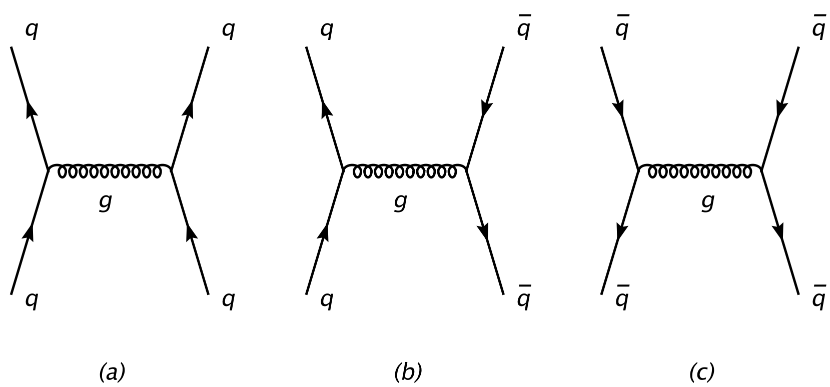

Fig. 3: Gluon virtual exchanges between quarks qq, quarks and anti-quarks $q\bar{q}$, and also between anti-quarks $\bar{q}\bar{q}$.

In the case of toponium the contributions of the Higgs scalar particles are essential, but less than gluon interactions. Toponium is very unstable due to the decay of the top quark itself.

However, putting more and more top and anti-top quarks together in the lowest energy bound states, we notice that attractive Higgs forces continue to increase. Simultaneously gluon (attractive and repulsive) forces first begin to compensate themselves, but then begin to decrease relatively to the Higgs effect with the growth of the number of NBS constituents t and $\bar{t}$. The Higgs exchange binding energy for the whole system becomes proportional to the number of pairs $t\bar{t}$, rather than to the number of constituents.

The maximum of the special binding energy value ϵ (the binding energy per top or anti-top) corresponds to the $1S$-wave NBS $6t + 6\bar{t}$.

The explanation is given as follows: top-quark has two spin states (two spin degrees of freedom corresponding to the two projections of the spin $\frac{1}{2}$) and three states of colors. This means that, according to the Pauli principle, only $2 \times 3 = 6t$-quarks can be in a $1S$-wave function. Then we can have also $6\bar{t}$-quarks. So we deal with the 12 quark (or anti-quark) constituents, that is, with 6 pairs of $t\bar{t}$, which simultaneously can exist in the $1S$-wave state. If we try to add more top-constituents $t\bar{t}$, then some of them will turn out to the $2S$-wave, and the NBS binding energy will decrease at least 4 times. For P-,D-, etc. waves the NBS binding energy decreases more and more.

3 T-ball mass estimate

The mass of T-ball containing the number $N_{\text{const.}}$ of top and anti-top quarks is:

$$M_T = N_{\text{const.}} M_t - E_T = N_{\text{const.}} (M_t - \epsilon) \text{ GeV}, \tag{1}$$

where M_t is the top-quark pole mass, E_T is a total binding energy and $\epsilon = E_T/N_{const.}$ presents the specific binding energy.

Below we use the following notation: the scalar NBS $6t + 6\bar{t}$, having the spin $S = 0$, is named as T_s-ball. And T_f-ball presents the NBS $6t + 5\bar{t}$, which is a fermion. Here $\overline{T_f} = 5t + 6\bar{t}$.

3.1 T_s-ball mass estimate.

According to the Particle Data Group [13], the top-quark mass is

$$M_t = 172.6 \pm 1.4 \text{ GeV}, \tag{2}$$

therefore the mass of the T_s-ball is given by the following expression:

$$M_T = 12M_t - E_T = 12 \cdot (172,6 - \epsilon) \text{ GeV}. \tag{3}$$

With aim to estimate the binding energy E_T of the NBS $6t + 6\bar{t}$, first we will determine the binding energy of the single top-quark relatively to the remaining 11 quarks, which we

shall call nucleus. Assuming, that the radius of this nucleus is small enough in comparison with the Compton wave length of the Salam-Weinberg Higgs particle, we are able to use the usual Bohr formula for the binding energy of the Hydrogen atom, replacing the electric charge e into the top-quark Yukawa coupling constant (YCC) $g_t/\sqrt{2}$.

Here we use the normalization, in which the kinetic energy term of the Higgs field Φ_H and the top-quark Yukawa interaction are given by the following Lagrangian density:

$$L = \frac{1}{2} D_\mu \Phi_H D^\mu \Phi_H + \frac{g_t}{\sqrt{2}} \overline{\psi_{tL}} \psi_{tR} \Phi_H + h.c. \tag{4}$$

In this case the attraction between the two top (anti-top) quarks is presented by the potential similar to the Coulomb one:

$$V(r) = -\frac{g_t^2/2}{4\pi r}. \tag{5}$$

It is easy to see that the attraction between any pairs tt, $t\bar{t}$, $\overline{tt}$ is described by the same potential (5).

Now we can estimate the binding energy of a single top-quark relatively to the nucleus having $Z = 11$. However, if we want to obtain the total potential energy of the system, we must think of bringing the quarks or anti-quarks into the bound state one by one. So, instead of taking the potential for NBS:

$$V(r) = -\frac{11 g_t^2/2}{4\pi r} \tag{6}$$

we should take an average over the steps of putting in the particles one by one and use the potential [4]:

$$V(r) = -\frac{\frac{11}{2} g_t^2/2}{4\pi r}. \tag{7}$$

Using the well-known equation for the n energy level of the Hydrogen atom, we have:

$$E_n = -\left(\frac{Z g_t^2/2}{8\pi}\right)^2 \frac{M_t^{(\text{reduced})}}{2n^2}. \tag{8}$$

Here $M_t^{(\text{reduced})}$ is the top-quark reduced mass:

$$M_t^{(\text{reduced})} = \frac{Z M_t}{Z+1}, \tag{9}$$

and we obtain the following equation:

$$E_n = -\left(\frac{Z g_t^2/2}{8\pi}\right)^2 \frac{Z M_t}{2(Z+1)n^2}. \tag{10}$$

The level with $n = 1$ corresponds to the ground $1S$-wave state, e.g.

$$E_1 = -\left(\frac{11 g_t^2}{16\pi}\right)^2 \frac{11 M_t}{24}. \tag{11}$$

A total binding energy of T_s-ball, containing the 12 particles, can be obtained by adding the binding energy of the remaining constituents, that is, by multiplying the formula (11) with a general number of constituents, e.g. 12, taking into account a duplication.

Finally, in this non-relativistic case the value of the total binding energy is equal to:

$$E_T = 6\left(\frac{11g_t^2}{16\pi}\right)^2\frac{11M_t}{24} = \left(\frac{11g_t^2}{8\pi}\right)^2\frac{11M_t}{16}. \tag{12}$$

However, by analogy with a Hydrogen-like atom, we have considered only t-channel exchange by the Higgs bosons between the two top (or anti-top) quarks in the system of the NBS.

Let us consider now u-channel exchange.

¿From the first point of view, it is expected the absence of the difference between the quarks of different colors. But if we consider a formalism, in which both degrees of freedoms (colors and spin states of quarks) are fixed, then the NBS $6t + 6\bar{t}$ is completely antisymmetric under the permutation of its color and spin states. In this case, we can easily estimate u-channel contributions. Assuming that the NBS is antisymmetrized in such a manner, we formally consider a quark as a particle having no degrees of freedom. In this case, we shall take into account "minus" under the permutation of two quarks. It is natural, that in this approach a quark plays a role of a boson, but not a fermion.

A simple estimate of the u-channel Higgs exchange contribution [4] gives, instead of Eq. (7), the following averaged potential:

$$V(r) = -\frac{\frac{16}{2}g_t^2/2}{4\pi r}. \tag{13}$$

And the total binding energy is equal to:

$$E_T = -12\cdot(16/11)^2E_1 = \frac{11g_t^4}{2\pi^2}M_t. \tag{14}$$

Including the t-channel gluon exchange forces [4], we must correct the potential (7) by substituting

$$4g_t^2 \to 4g_t^2 + \frac{4}{3}g_s^2, \tag{15}$$

where QCD coupling constant g_s is given by its fine structure constant value at the EW-scale [13]:

$$\alpha_s(M_Z) = g_s^2(M_Z)/4\pi \approx 0.118. \tag{16}$$

The total averaged potential is now:

$$V(r)|_{tu-chan.,gluon} = -\frac{4g_t^2 + \frac{4}{3}g_s^2}{4\pi r}, \tag{17}$$

and the total binding energy is given by the following expression:

$$E_T = \frac{11(g_t^2 + \frac{1}{3}g_s^2)^2}{2\pi^2}M_t. \tag{18}$$

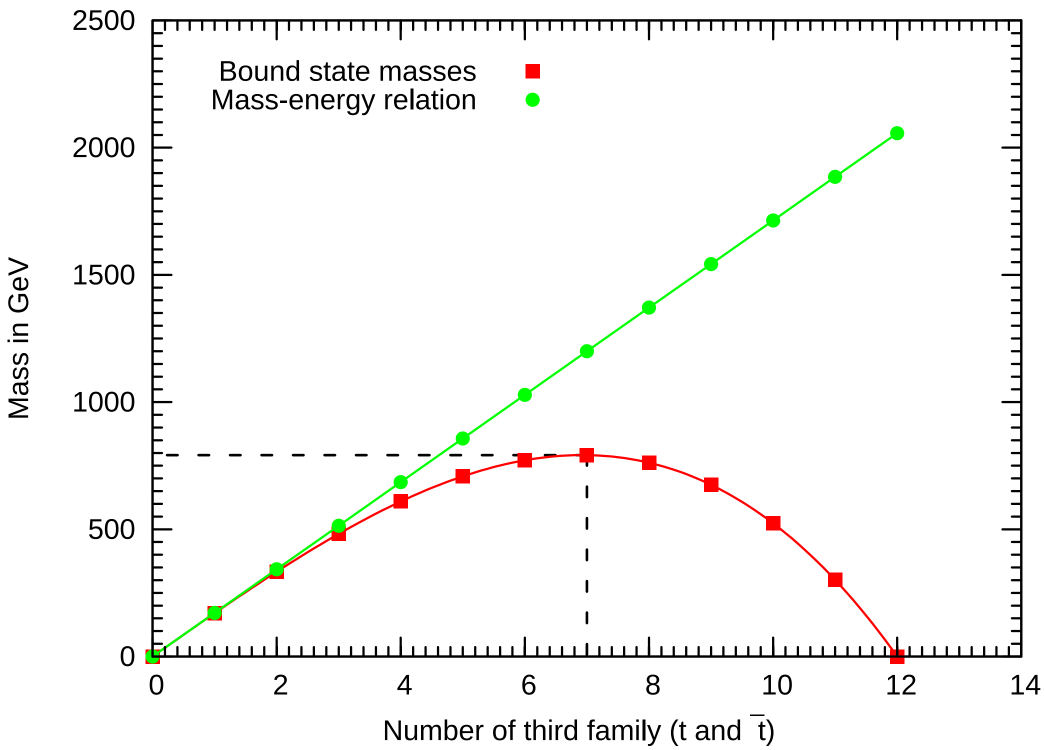

Fig. 4: The dependence of the T-ball's mass of the number $N_{\text{const.}}$ of the NBS constituents.

Considering a set of Feynman diagramms (e.g. the Bethe-Salpeter equation), we obtain the following Taylor expansion in g_t^2 for the mass of the NBS T_s, containing 12 top-anti-top quarks:

$$\begin{aligned} M_T^2 &= (12M_t)^2 - 2(12M_t)E_T + ... \\ &= (12M_t)^2(1 - \frac{11}{12\pi^2}(g_t^2 + \frac{1}{3}g_s^2)^2 + ...). \end{aligned} \tag{19}$$

In general, the binding energy of the top-quark in the NBS depends on the number of the NBS constituents $N_{\text{const.}}$, and is proportional to the following expression:

$$E_{\text{binding}} \propto \frac{1}{2}N_{const.}(N_{const.} - 1). \tag{20}$$

The dependence of the T-ball's mass of $N_{\text{const.}}$ is given by Fig. 4.

Approximately this dependence is described by the following equation:

$$M_T = M_{NBS} = M_t \cdot N_{\text{const.}}(1 - \frac{N_{\text{const.}}^2}{12^2}). \tag{21}$$

3.2 T_f-ball mass estimate

One of the main ideas of the present investigation is to show that the Higgs interaction of the 11 top-anti-top quarks creates a T_f-ball – a new fermionic bound state $6t + 5\bar{t}$, which is similar to the t'-quark of the fourth generation.

According to the formula (21), we obtain an estimate of the mass of T_f-ball $6t+5\bar{t}$, using Particle Data Group result (2):

$$M_{T_f} \approx (172,6)\cdot 11\cdot 0.16\ \ GeV \simeq 300\ \ GeV. \tag{22}$$

This is a very crude estimate, which does not exclude the mass $M_{T_f} > 300$ GeV.

At present, a lot of physicists, theorists and experimentalists, are looking forward to the New Physics. However, it is quite possible that LHC will show only the 'Bjorken-Rosner nightmare': only the Salam-Weinberg Higgs boson could be discovered and nothing more. Nevertheless, the T-balls calculated in the framework of the SM could exist.

4 The calculation of the top-quark YCC at the two phases border

In our normalization we obtain the following expression for the top-quark mass by the Salam-Weinberg theory:

$$M_t = \frac{g_t}{\sqrt{2}}v \approx 174 g_t \text{ GeV}, \tag{23}$$

where $v = 246$ GeV is a VEV of the Higgs field in the EW-vacuum: $<|\Phi_H|>= v$.

Using the experimental value of the top-quark mass (2), we obtain:

$$g_t \approx \frac{M_t}{v/\sqrt{2}} \approx (172.6\pm 1.4)/174.5 \approx 0.989\pm 0.008. \tag{24}$$

We see that the top-quark YCC is of order of unity at the EW-scale.

If the NBS is a bubble in the EW-vacuum and contains 12 top-like constituents insight this bubble having a value $<|\Phi_h|>$, which is smaller than $<|\Phi_H|>= 246$ GeV [6], then the light scalar Higgs bosons with mass $m_h < M_H$ (here M_H is the experimental Higgs mass) can bind these top-like quarks so strongly that finally we can obtain the Bose-Einstein condensate of T-balls – a new vacuum at the EW-scale. Indeed, it is quite possible: for example, if g_t increases when the number of top-quarks in the T-ball grows, then the binding energy compensates the NBS mass $12m_t$ in the T_s-ball so strongly that the mass M_{T_s} becomes almost zero, and even tachyonic, e.g. $M^2_{T_s} < 0$, what leads to the formation of the scalar T-balls' condensate in the new vacuum. The result $g_t \sim 1$ means that the experimentally observed value of the top-quark YCC belongs to the border of the two phases – with and without T-balls' condensate. The value of the mass m_h, which corresponds to the Higgs field insight the NBS [6], can just coincide with estimates given by Refs. [14] and [15]: $\max(\mathrm{m_h}) = 29$ Gev in [14], what gives $\max <|\Phi_\mathrm{h}|>= 62$ GeV insight NBS, and correspondingly $\max(\mathrm{m_h}) = 49$ Gev in [15], what corresponds to $\max <|\Phi_\mathrm{h}|>= 105$ GeV, if the Higgs pole mass is $M_H = 115$ Gev, what is close to the LEP2 result $M_H = 114.4$ Gev. The value of the top-quark mass $m_t < M_t$ is obtained with the same Higgs field Φ_h insight the NBS bubble.

The condition $M_T^2 = 0$ corresponds to the new phase transition border. Using (16), we obtain from Eq. (19) the following result:

$$M_T^2 = (12m_t)^2 - 2(12m_t)E_T + ...$$

$$= (12m_t)^2(1 - \frac{11}{12\pi^2}(g_t^2 + \frac{1}{3}g_s^2)^2 + ...) \approx (12m_t)^2(1 - 0.092_{88}(0.4565 + g_t^2)^2) = 0, \quad (25)$$

or [4]

$$g_t|_{phase\ transition} \approx 1.68. \quad (26)$$

At this level we have considered only t- and u-channels of the Higgs and gluon exchange, also only t and $\bar{t}$ as NBS constituents. We have not included W-boson or 'eaten' Higgs exchanges, which lead to the existence of b-quarks as constituents.

5 Contributions of b-quarks in the "b-replaced NBS"

Up to the year 2008, we were sure that only t- and $\bar{t}$-quarks are the constituents of T-balls. But at present we know that we can take into account considerable contributions of left b-quarks (see Refs. [4, 10]).

If we had no $b\bar{b}$-quark pairs in T-balls, then there would be an essential superposition of different states of the weak isospin. The presence in the condensate of the not pure singlet states of the EW-theory could create serious problems. But including b-quarks in the NBS, we shall obtain the dominance of the isospin singlets of EW-interactions only, and even if we have the phase with $< |\Phi_T| > \neq 0$ (here Φ_T is the T_s-ball field), it can be considered without any problems, in agreement with the SM LEP precision data.

With the inclusion of both b- and t-quarks we think of a more weak isospin invariant picture, and it becomes natural to think of replacing one (or several) of t-quarks in the NBSs by b-quark(s).

There is a simple way to estimate the mass of the NBS with one t replaced by a b, what we called "b-replaced NBS". We know that b-quarks does not interact significantly (in the first approximation) with the NBS. Thus we can add a b-quark (or anti-b-quark) to the NBS "11" without changing the energy, or mass. Then the "b-replaced" scalar NBS still would have a mass very close to "11" NBS M_{T_f}, say, of the order of 400 GeV, by our estimate (22). It is a boson:

$$T_s(b - \text{replaced}) = b + 5t + 6\bar{t}. \quad (27)$$

We have also:

$$T_s(\bar{b} - \text{replaced}) = 6t + \bar{b} + 5\bar{t}. \quad (28)$$

The NBSs (27) and (28) will have approximately the same mass.

Of course, we also can consider the fermionic b-replaced NBS:

$$T_f(b - \text{replaced}) = b + 5t + 5\bar{t}, \quad (29)$$

and

$$\overline{T_f}(\bar{b} - \text{replaced}) = 5t + 5\bar{t} + \bar{b}. \tag{30}$$

In general case we can construct:

$$T_s(n_b b - \text{replaced}) = n_b b + (6t + 6\bar{t} - n_b t), \tag{31}$$

and

$$T_s(n_{\bar{b}}\bar{b} - \text{replaced}) = n_{\bar{b}}\bar{b} + (6t + 6\bar{t} - n_{\bar{b}}\bar{t}). \tag{32}$$

Correspondingly we can obtain:

$$T_f(n_b b - \text{replaced}) = n_b b + (6t + 5\bar{t} - n_b t), \tag{33}$$

and

$$\overline{T_f}(n_{\bar{b}}\bar{b} - \text{replaced}) = n_{\bar{b}}\bar{b} + (5t + 6\bar{t} - n_{\bar{b}}\bar{t}). \tag{34}$$

They will have a mass > 400 GeV (see Fig. 4).

In general case we can construct:

$$T_s(n_b b - \text{replaced}) = n_b b + (6t + 6\bar{t} - n_b t), \tag{35}$$

and

$$T_s(n_{\bar{b}}\bar{b} - \text{replaced}) = n_{\bar{b}}\bar{b} + (6t + 6\bar{t} - n_{\bar{b}}\bar{t}). \tag{36}$$

Correspondingly we can obtain:

$$T_f(n_b b - \text{replaced}) = n_b b + (6t + 5\bar{t} - n_b t), \tag{37}$$

and

$$\overline{T_f}(n_{\bar{b}}\bar{b} - \text{replaced}) = n_{\bar{b}}\bar{b} + (5t + 6\bar{t} - n_{\bar{b}}\bar{t}). \tag{38}$$

These more heavy T-balls with $M_T > 400$ GeV will have smaller cross-sections of their production, because they are less strongly bound and can a less extend to be considered approximately fundamental particles.

The more accurate estimate given in Ref. [4] predicts the existence of "11" and "10" constituent bound states with masses approximately 760 and 960 GeV, respectively.

6 Main corrections to the calculation of the top-quark YCC at the new phase border

In this section we present main corrections to the value of the top-quark YCC given by Eq. (27) at the border of the two phases I and II:

I) Phase-I has not the Bose-Einstein condensate of T_s-balls. In this phase the VEV of the T_s-ball's scalar field Φ_T is equal to zero: $< \Phi_T >= 0 >$.

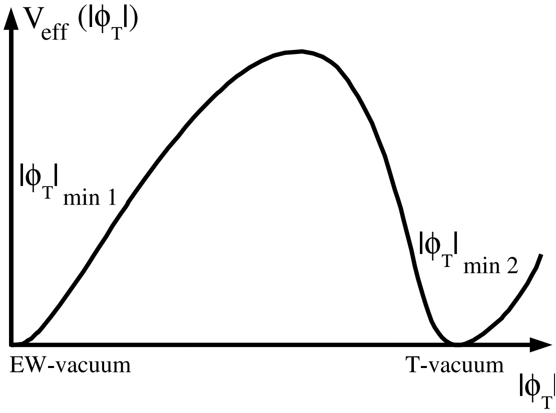

Fig. 5: The effective potential $V_{\text{eff}}(|\Phi_T|)$, depending on the norm of the T_s-ball's scalar field Φ_T, has two minima: at $\Phi_T = 0$ (EW-vacuum) and at $\Phi_T \neq 0$ (T-vacuum).

II) Phase-II contains such a condensate and $< \Phi_T > \neq 0 >$.

The effective potential $V_{\text{eff}}(|\Phi_T|)$, depending on the norm of the T_s-ball's scalar field Φ_T, is presented in Fig. 5.

We have seen in Section 4 that the main requirement of the appearance of the new phase of the condensed T_s-balls is a condition:

$$m^2_{NBS} = M^2_{T_s} = 0.$$

Using Eq. (26), which describes the square mass of the scalar fireballs, we have obtained the estimate (27) of the YCC value of top-quark at the border of the two phases I and II [4]. But in this case we have ignored weak gauge bosons exchanges, what is not true. The longitudinal components of W- and Z_0- bosons really represent the so-called "eaten" Higgs components (see [4]), and it is necessary to take them into account.

The Higgs field has two complex components. So far there are three more real fields in the Higgs doublet. The components "eaten" by weak gauge bosons are the Higgs charged fields. As a result, weak gauge bosons when exchanged from top-quark convert it into a b-quark or oppositely. The particles which couple sufficiently stronger are the *left-handed b-quarks*. Including virtual left-handed $b\bar{b}$-pairs and the "eaten" Higgses, Ref. [4] have presented the following correction to the predicted value of g_t at the new phase

border corresponding to the zero mass T_s-ball:

$$g_t|_{phase\ transition} \approx 1.68/4^{1/4} \approx 1.18. \tag{39}$$

On top of that we then have the following corrections listed:

1) The first correction comes from gluon interactions if we take into account simultaneously the Higgs and gluon interactions of top-quarks in all (s-, t-, u-) channels.

2) The correction from the one-loop interaction of top-quarks.

3) The correction due to that the effective Higgs mass m_h is not zero - as we first calculate with - but rather varies as a function of the distance r from the center, first reaching the normal effective Higgs mass value — say, the LEP finding value $m_H \cong 115$ GeV — in the outskirts of the T-ball.

4) Relativistic corrections.

5) Renormgroup corrections.

6) The corrections from many body effects — from the contributions of not only one-, but n-Higgs-bosons.

In general, all corrections lead to the accuracy 15% and according to Ref. [4] give the following result:

$$g_t|_{phase\ transition} = 1.01 \pm 0.15. \tag{40}$$

This result is to be compared with the experimental value (24) obtained from a top quark pole mass of 172.6 ± 1.4 GeV [13]. The prediction has only ≈ 0.5 standard deviations.

Here we comment that all calculations in Ref. [4] are in agreement with calculations of Ref. [14].

As it was shown in Refs. [3–8], the further increasing of YCC g_t can give:

$$M^2_{T_s} < 0,$$

and T-balls begin to condense forming a new phase of the SM — the phase of the condensed scalar T_s-balls.

7 New phases of the SM

Now we are in confrontation with a question: do the new phases of the SM exist? Are they different from the well-known Salam-Weinberg Higgs phase? Does a phase of the condensed T_s-balls exist?

The answer on this question is related with the SM parameters.

7.1 Three EW phases of the SM

Taking into account seriously our results in the estimates of g_t and M_T, we can have three phases – three vacua of the SM at the EW-scale:

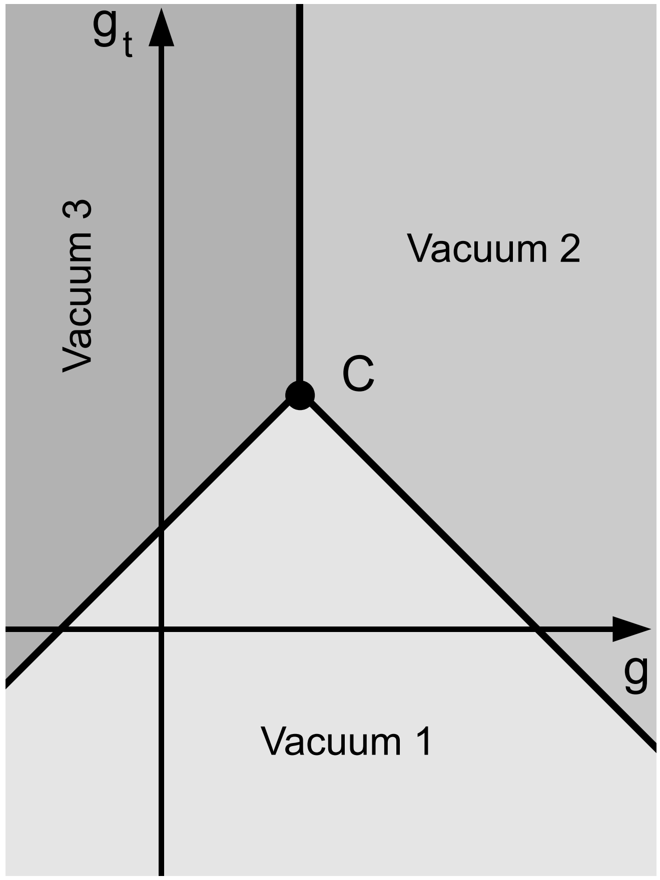

Fig. 6: A symbolic phase diagram for the SM at the EW-scale.

I) $< \Phi_H > \neq 0, < \Phi_T >= 0$ — "Vacuum 1", the phase in which we live;

II) $< \Phi_H > \neq 0, < \Phi_T > \neq 0$ — "Vacuum 2";

III) $< \Phi_H >= 0$, $< \Phi_T > \neq 0$ — "Vacuum 3",

which are presented symbolically by the phase diagram of Fig. 6.

Fig. 6 shows the critical point C (triple point), in which the SM three phases meet together: this triple point is similar to the critical point considered in thermodynamics where the density of the vapor, water and ice are equal (see Figs. 7,8).

The existence of the new phases near the EW-scale can solve the problem of hierarchy. Here we recall the Multiple Point Principle (MPP) suggested in Refs. [16–23].

7.2 The fundamental (Planck) scale of the SM

A priori it is quite possible for a quantum field theory to have several minima of its effective potential as a function of its scalar fields Φ (exactly speaking of its norm $|\Phi|$).

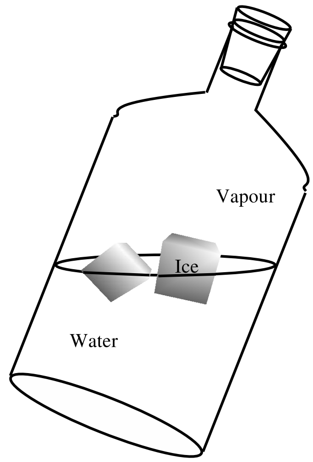

Fig. 7: Vapor, water and ice in the critical state.

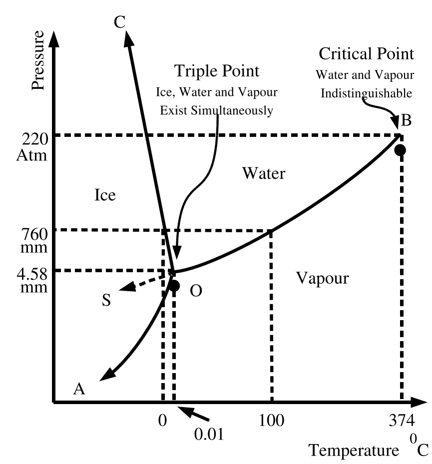

Fig. 8: Critical point considered in thermodynamics: the densities of the vapor, water and ice are equal.

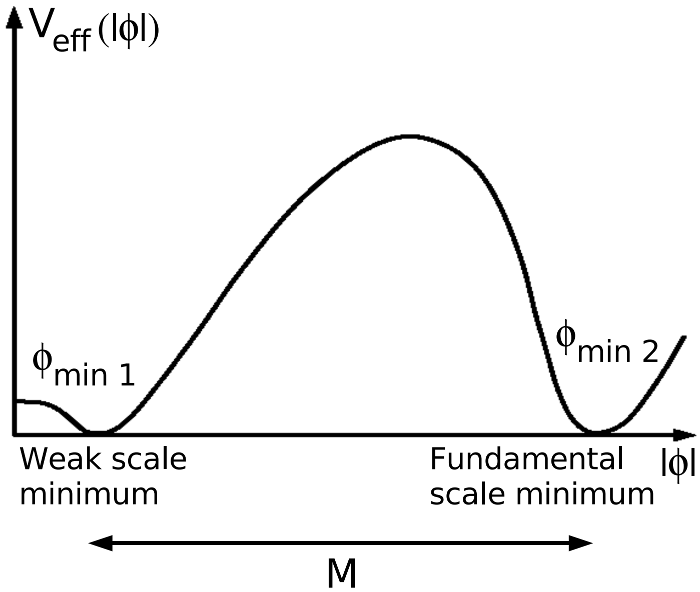

Fig. 9: The first (our) vacuum at $|\Phi| \approx 246$ GeV and the second vacuum at the fundamental scale $|\Phi| \sim M_{\rm Pl}$.

These minima can be degenerate. Moreover, it is assumed that all vacua existing in Nature (there can be a number of several vacua) are degenerate and have the same zero, or almost zero, vacuum energy densities which coincide with the cosmological constant Λ determined by Einstein. This is confirmed by the phenomenological cosmology.

According to the MPP, the SM has the two minima of its effective potential considered as a function of the variable $|\Phi|$, where $\Phi = \Phi_H$. These minima are degenerate and have $\Lambda = 0$:

$$V_{\rm eff}|_{min1} = V_{\rm eff}|_{min2} = 0, \tag{41}$$

$$\mathbf{V'_{\rm eff}|_{min1} = V'_{\rm eff}|_{min2} = 0}, \tag{42}$$

what is shown in Fig. 9.

It is assumed that the second minimum exists near the Planck scale:

$$|\Phi_{min2}| \sim M_{\rm Pl}.$$

This is a fundamental scale.

The calculation of the NBS mass have used only the SM parameters. The MPP determines the coupling constants in the SM and therefore — the structure of the NBSs $T_{s,f}$. Since at the border of the two phases I and II the top-quark YCC leads to zero mass of the NBS T_s, we can assume that the MPP manifests the phase transitions in the SM in such a way that we have the finetuning in the SM, which solves the hierarchy problem.

The MPP calculations of gauge coupling constants were obtained recently in Refs. [24, 25].

8 The Tevatron-LHC experiments searching for W, Z, t, t' and different jets

This investigation is devoted to the main purpose of the experiment – to search for the Higgs boson, and in this connection to search for T-balls, just what we were considering as the b-replaced NBSs.

¿From the beginning, we have considered the following NBSs:

$$6t + 6\bar{t}, \qquad 6t + 5\bar{t}.$$

First of these NBS is a scalar boson T_s, and the second one is a fermion T_f with quantum numbers of t-quark, which is difficult to distinguish from the quark of the fourth generation.

A typical process which is observed at the Tevatron ($p\bar{p}$-collisions, $\sqrt{s} \simeq 1.96$ GeV) is shown in Fig. 10. Unfortunately, the cross-section for the Higgs boson production at the Tevatron is predicted to be rather small and sufficient data for a discovery of H is unlikely to be collected before the date when more powerful LHC experiment begins to work in 2009.

There are several Higgs production methods at the LHC, which lead to the observable Higgs production cross-sections $\sigma(pp \to HX)$. These include:

- gluon-gluon fusion;
- WW and ZZ fusion;
- Associated production of W and Z bosons;
- Associated production of $t\bar{t}$, or $t'\bar{t}'$.

Typical Feynman diagrams for the signal and background processes are shown in Figs. 11 and 12.

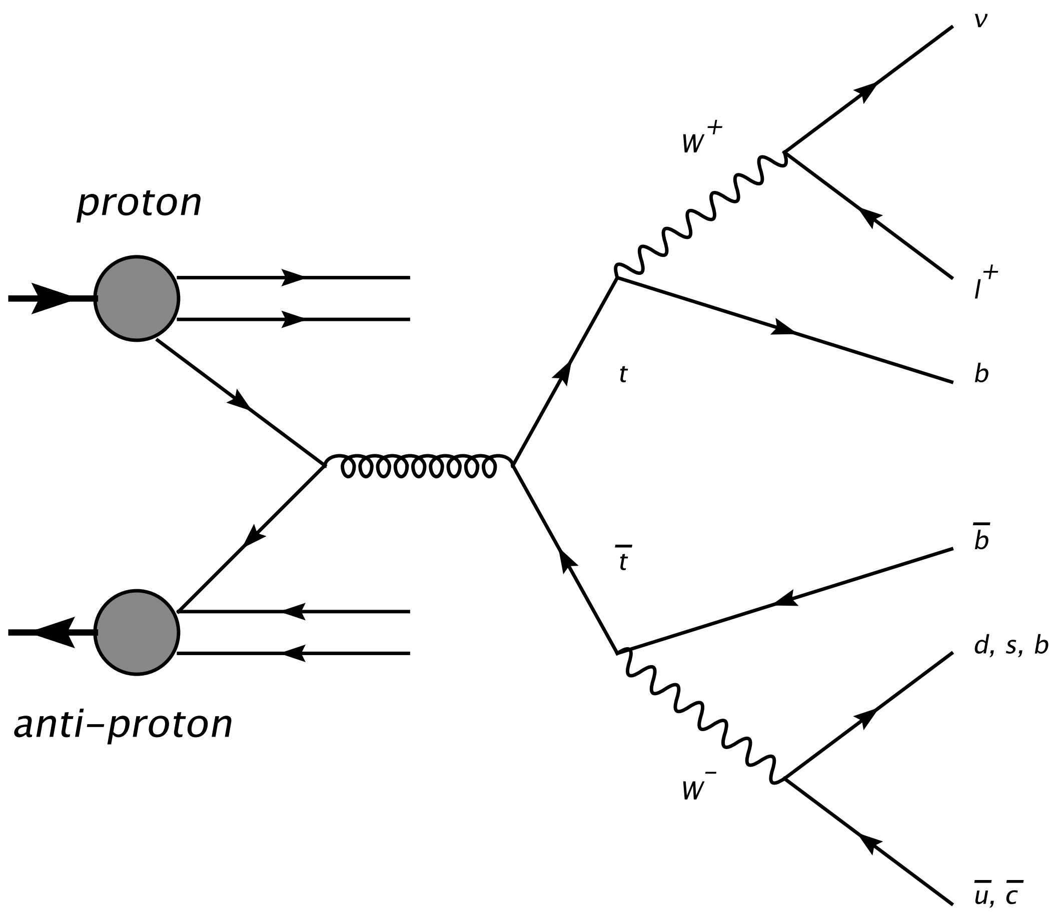

Fig. 10: A typical process observed at the Tevatron in $p\bar{p}$ collisions.

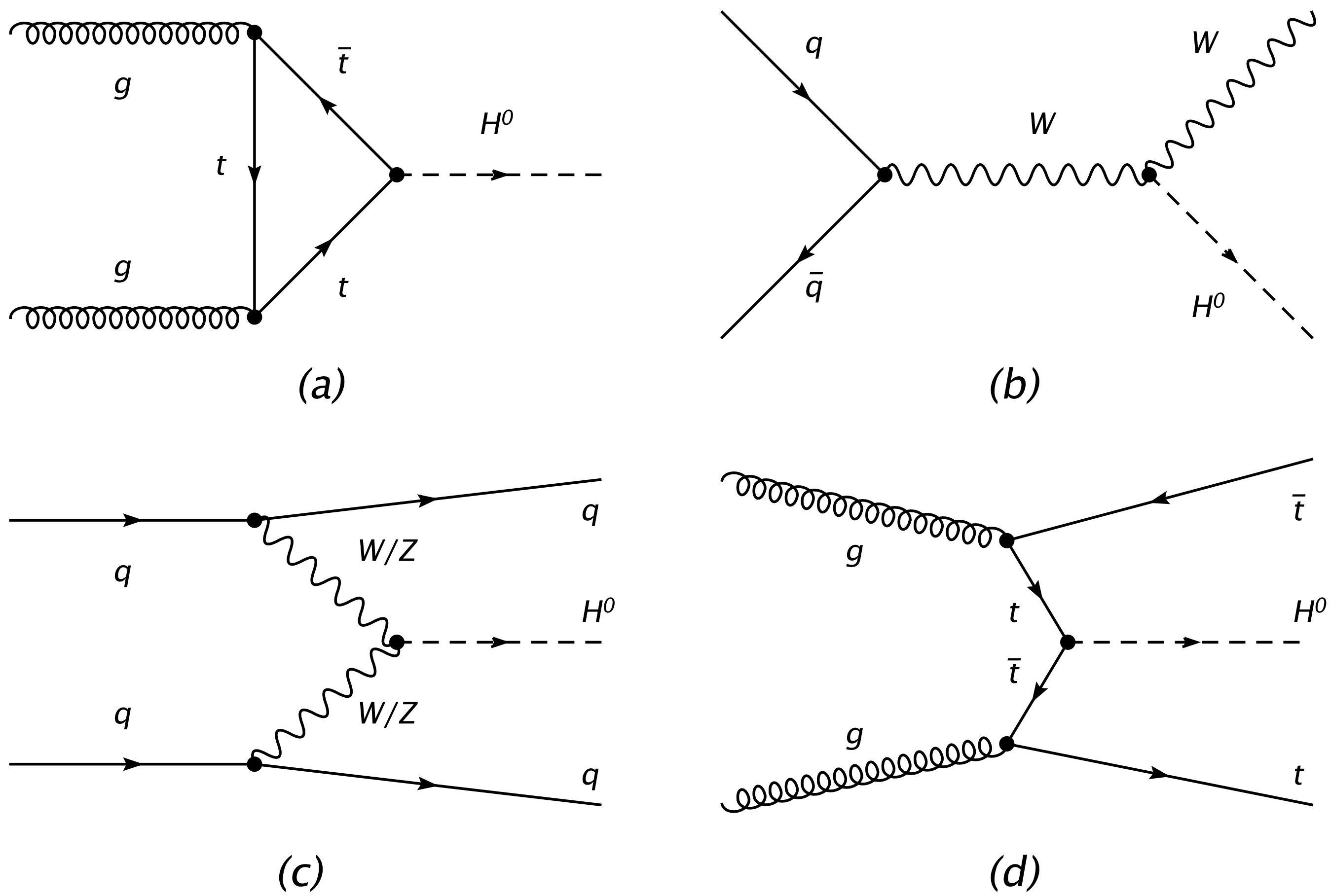

Fig. 11: Feynman diagrams for the processes (a) $gg \to t\bar{t}H^0$, (b) $q\bar{q} \to t\bar{t}H^0$, (c) $gg \to t\bar{t}b\bar{b}$, (d) $gg \to Z/W/\gamma^* \to H^0(t\bar{t}\ \ or\ \ b\bar{b})$.

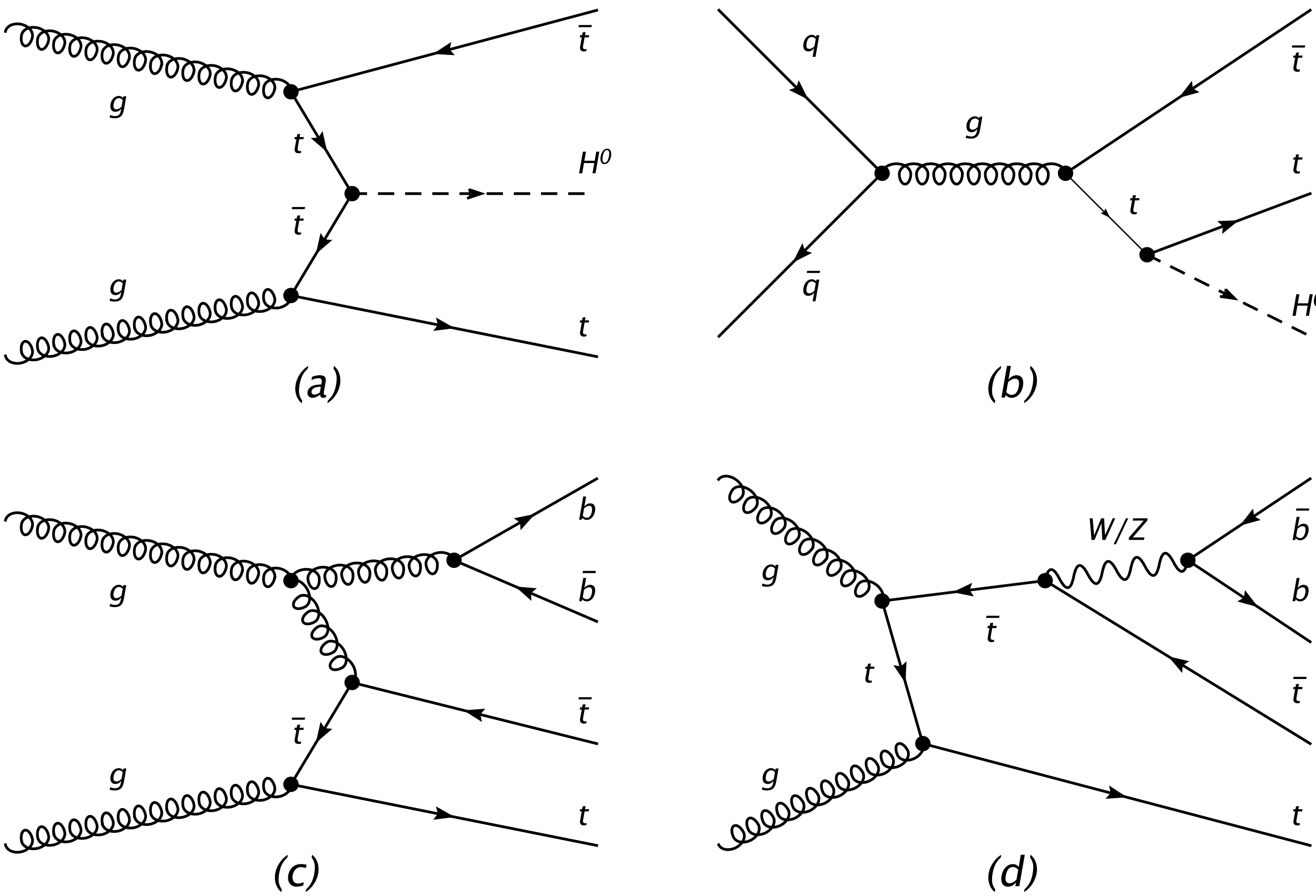

Fig. 12: Feynman diagrams for the production of leptons and jets.

At the LHC, $t\bar{t}H^0$ is produced 90% of the time via a gluon-gluon interaction and only by a qq-interaction in the remaining 10%. Once produced, a top-quark decays almost exclusively to the W-boson and b-quark. W-bosons decay hadronically about 2/3 of the time, producing two jets in the final state.

The branching ratios for these processes are shown in the Table 1:

Table 1

$$\mathbf{t \to Wb} \qquad \mathbf{0.998},$$

$$\mathbf{W \to l\nu} \qquad \mathbf{0.108},$$

$$\mathbf{W \to hadrons} \qquad \mathbf{0.676},$$

$$\mathbf{t\bar{t} \to l\nu bjj\bar{b}} \qquad \mathbf{0.291}.$$

The final state with the highest branching fraction is where both top-quarks decay hadronically, producing light-jets and two b-jets. When the decay of the Higgs boson to the two b-quarks is taken into account, this produces a purely hadronic final state. Requiring one of the W-bosons to decay leptonically produces a final state with four b-jets, two light-jets, one lepton missing momentum (see Fig. 13).

Only l and μ ($l = e,\ \mu$) are considered in this analysis.

9 Can we see T-balls at LHC or Tevatron?

At present, the first question is: can we observe the NBSs T-balls at LHC or Tevatron?

If the mean square radius of the T-ball is small in comparison with its Compton wave length:

$$r_0 \approx (\sqrt{2}M_t)^{-1} << \frac{1}{m_{NBS}}, \tag{43}$$

then the NBS can be considered as an almost fundamental particle. Then our NBS are strongly bound and can be observed at colliders. As t'-quark of the fourth generation the fermionic NBS T_f will belong to the fundamental representation $\underline{3}$ (color triplet).

What processes with the participation of T-balls have to play the main role in the experiments at colliders?

A) First, the possible decay mechanism:

$$H \to 2T_s, \tag{44}$$

if $M_{T_s} < m_H/2$.

Using limits given by the Tevatron experiments $115 \lesssim m_H \lesssim 160\ GeV$, we obtain the requirement for the Higgs decay mechanism to work (on shell):

$$M_{T_s} \lesssim 80\ GeV.$$

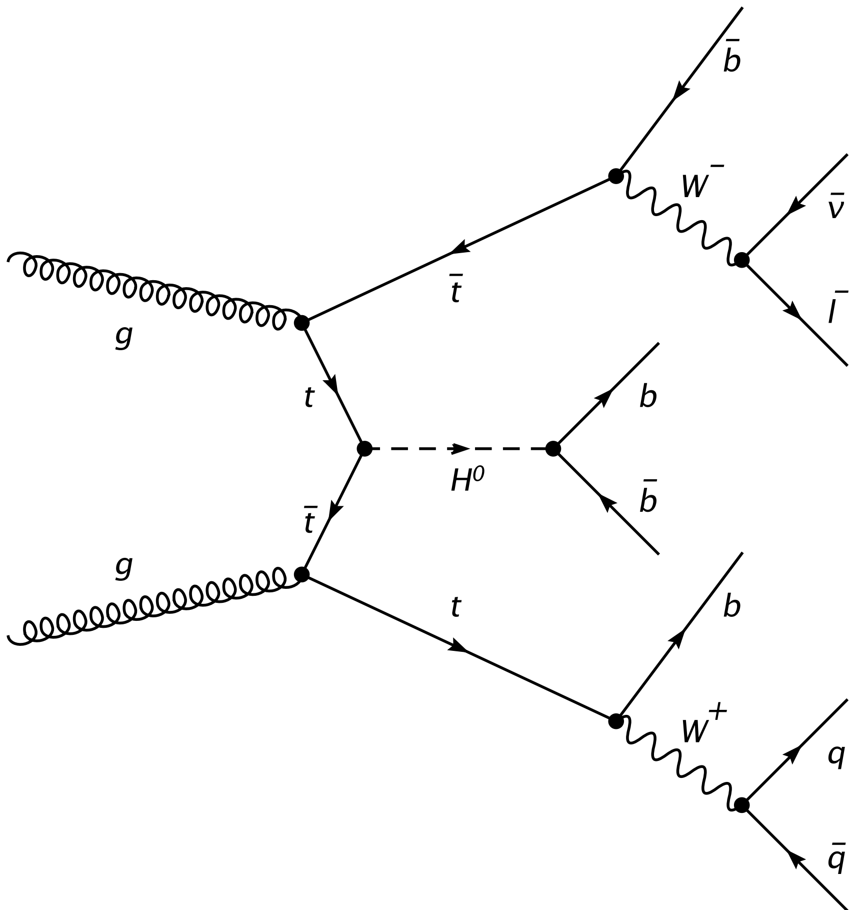

Fig. 13: Feynman diagrams for the production of leptons and jets with the intermediate Higgs boson.

If $M_{T_s} > \frac{1}{2}m_H$, then the decay (44) is absent in nature, and in the above-mentioned process the T_s-balls fly away forming jets. As a result, we have the production of hadrons with high multiplicity :

$$T_s(b - \text{replaced}) \to JETS.$$

Jets create a lot of hadrons [1] .

Since the coupling of H with T-balls is very strong, then the total decay width of the Higgs boson is enlarged due to the decays of H in T_s, while the decay width of H into leptons and photons (these channels are easily observed experimentally) is essentially less.

We see now that the present theory of T-balls predicts the observation of the Salam-Weinberg Higgs boson H as a broad peak at colliders.

B) Second, the all processes with the replacement $t\bar{t} \to T_f\overline{T_f}$ (see, for example, Fig. 10).

In the most optimistic cases the NBS $6t+5\bar{t}$ plays a role of the fundamental quark of the fourth generation, say, with mass $\simeq 300-400$ GeV, given by our preliminary estimate.

9.1 Two-gluon diagrams for the NBS production.

The "b-replaced NBS" $T_s(b - \text{replaced})$ cannot be produced simply in a pair by a gluon vertex, because it is a color singlet $\underline{1}$.

A pair $T_f\overline{T_f}$ of "11" NBS can be produced by a gluon, because it is a color triplet, and then "11" could make a rather soft emission of a b-quark and also a scalar "b-replaced NBS". But such a "soft b" emission may be difficult to detect at the Tevatron.

There also is an alternative idea (see Ref. [11]).

According to the idea by Li-Nielsen, the t or b emission and the scalar "b-replaced NBS" might be produced via the two gluons diagram with strong vertices: see, for example, the diagram given by Fig. 14.

The most important production mechanism for producing pairs of T_s-balls is two initial gluons that must be provided, say, from the Tevatron hadronic $p + \bar{p}$ collisions presented by Fig. 14.

According to the diagram of Fig. 14, the following decay is possible to observe at high energy colliders:

$$T_f(b - \text{replaced}) \to T_s + t + n_a b\bar{b},$$

since the mass of T_s is expected to be less than the T_f-mass.

Let us stress that if our description works, then the fermionic "b-replaced NBS" would make a perfect simulation of a fourth family t'.

It only deviates:

1) by needing either a more complicated diagrams for its production,

2) or by the emission of soft b-quarks,

[1] In Ref. [11] Li and one of us (H.B.N) have though argued that for the very light bound states the number of jets will be more moderate and the number of hadrons not so enormous again.

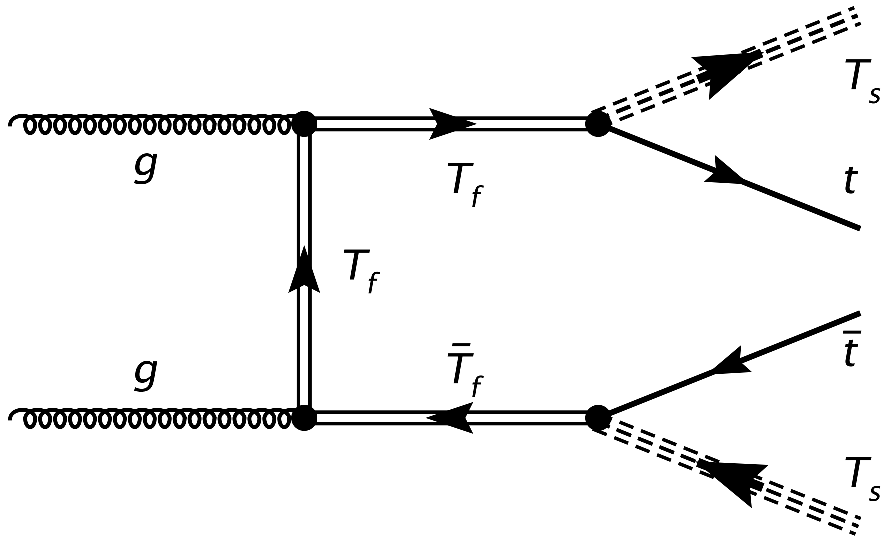

Fig. 14: Two gluon production of T_s-balls

3) or by simultaneously emitted a W-boson and T_s:

$$\text{"b-replaced"} \quad \text{NBS} \to T_s + W.$$

Now we take in our model the particle simulating the t': a fermionic "b-replaced NBS", for instance,

$$T_f(b - \text{replaced}) = 5t + b + 5\bar{t},$$

or

$$T_f(b - \text{replaced}, n_a b\bar{b}) = 5t + b + n_a b\bar{b} + 5\bar{t}, \quad \text{etc.}$$

So then we could really claim: *we expect that the Tevatron-LHC experiments should find either a fourth family t'-quark, or the fermionic "b-replaced NBS", or both of them.*

We have shown that the bound states $T_s(b - \text{replaced})$ and $T_s(b - \text{replaced}, n_a b\bar{b})$ can have masses very close to "11" NBS: $M_{T_f} \sim 300 - 400$ GeV, by our prediction. We also can consider more heavy "b-replaced" NBS (T-balls) with $M_T > 400$ GeV. All of them can be investigated at LHC.

Concerning how to distinguish the two hypotheses:

I) the true fourth family,

II) our bound state "b-replaced NBS",

we can immediately say: we do not expect exactly the same cross-section times branching ratio as that to be estimated for the true fourth family. Thus if the cross-section agrees extremely precisely with the calculation for a simple fundamental fourth family t'-quark, then it is suggested that our model is not the right explanation. However, if it is in the same range, but do not match perfectly, then it would support our model.

There are several deviations relative to genuine fourth family particles in the case of the "b-replaced NBS" particle production:

A) form-factors;
B) the soft b-emission;
C) some diagrams not having analogues in the fundamental t' production;
D) possibly alternative decays.

10 CDF II Detector experiment searching for heavy top-like quarks at the Tevatron.

Would we already have seen the production of the fermionic "11" NBS, called T_f, in colliders e.g. via it being transformed by b-exchange or emission into "b-replaced" NBS?

Recent experiments with CDF II Detector of the Tevatron [26, 27] do not exclude the existence of T-balls if the mass is over 300 GeV (see Figs. 15-18). Here we shall argue for that the very strange events, observed at the Tevatron as a fourth family t', which decays into a W and a presumed quark-jet, might in our model find another explanation: maybe it is the decay of a b-replaced NBS (T-ball) into a W and a gluon jet.

If our bound state T_s is indeed very light it would in practice at the high transverse momenta look much like just a jet, essentially indistinguishable from a quark or gluon jet. Thus the decay of a "b-replaced" NBS would just simulate the fourth family quark decaying to W and jet. The jet would just be a whole very light NBS.

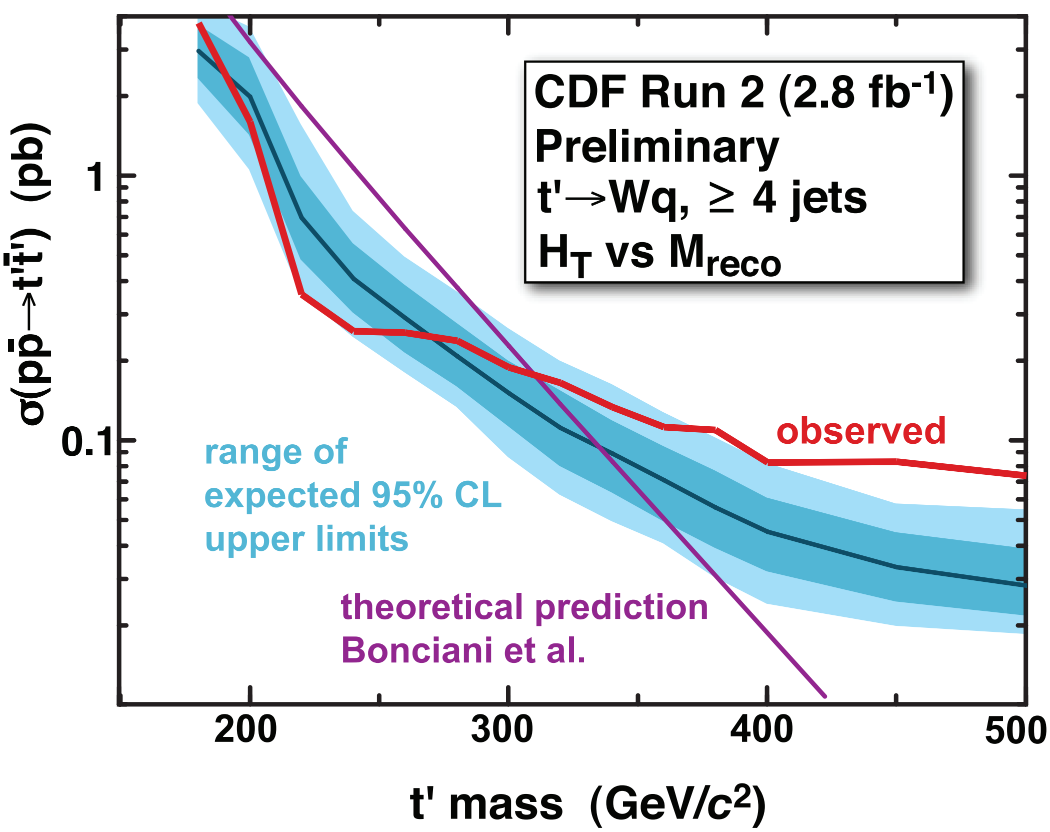

Fig. 15: Tevatron CDF-experiment: upper limit, at 95% CL, a fourth-generation t' quark with a mass below 300 GeV is excluded. Blue line presents a theoretical curve for the fourth-generation quarks cross-section.

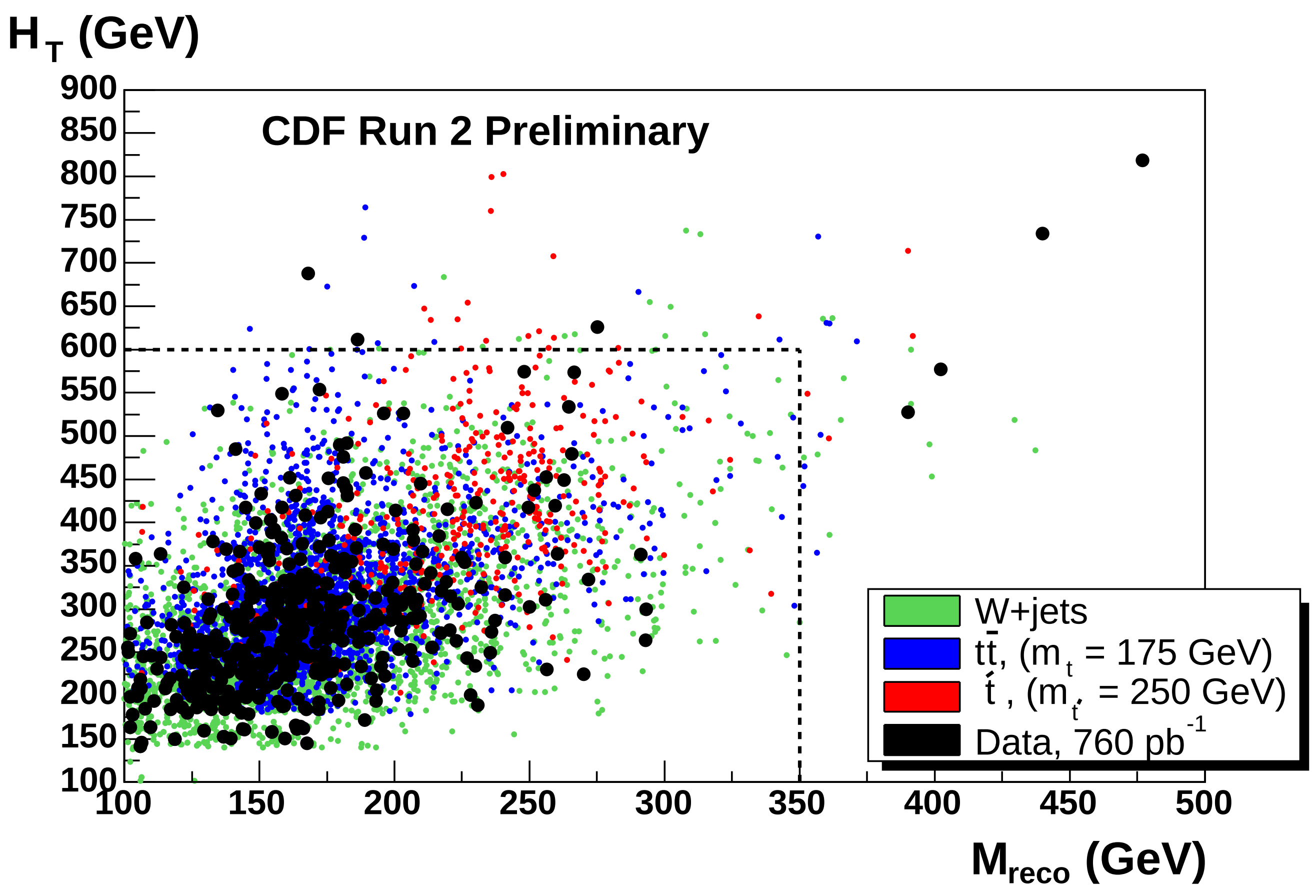

Fig. 16: Tevatron CDF-experiment: 2D distribution of H_T vs M_{rec} distribution showing the data (black points) and the fitted number of background events; QCD (purple circles), W+JETS (green squares) and $t'\bar{t}'$ (blue triangles). Here H_T is a total transverse energy in observed distribution, and M_{reco} is the reconstructed t' mass.

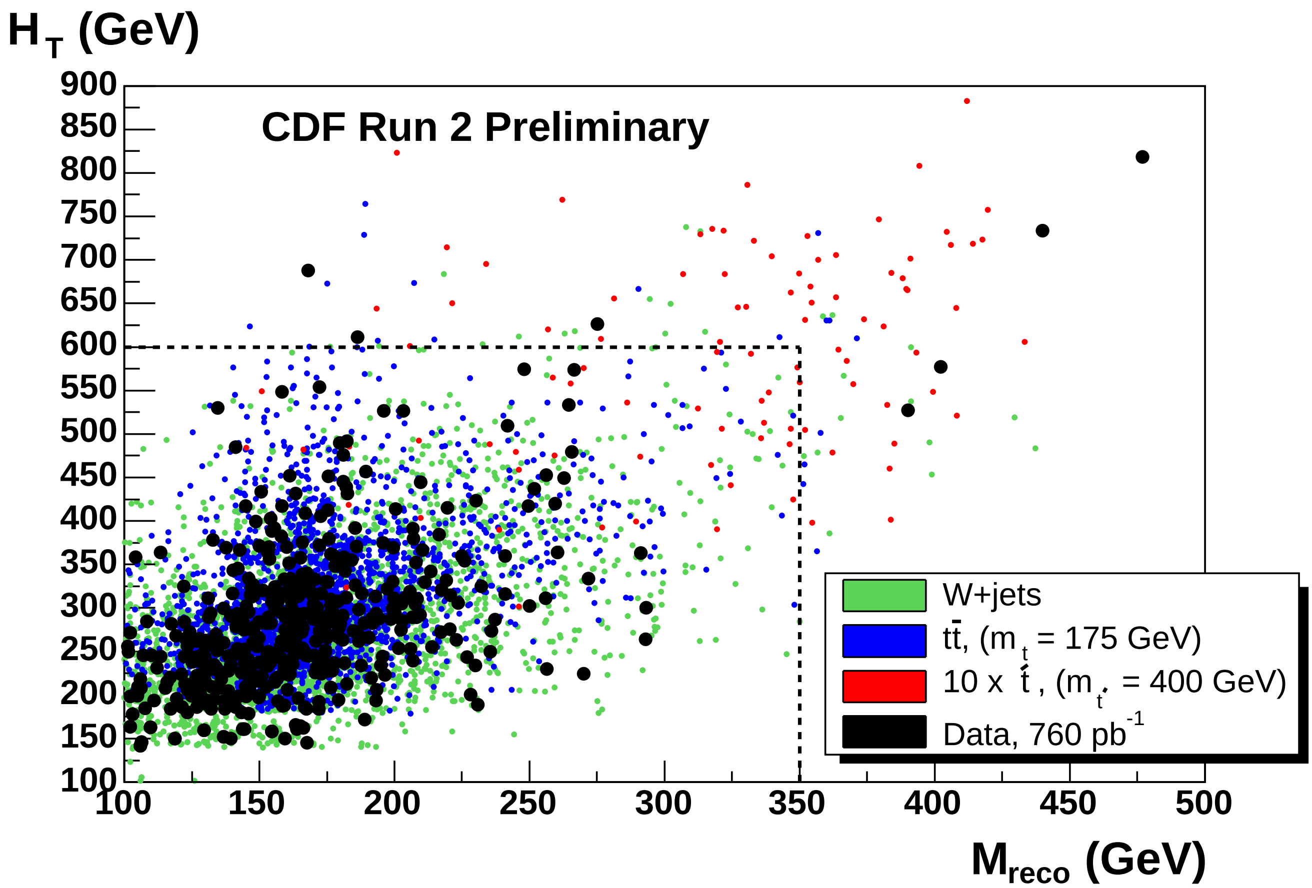

Fig. 17: Tevatron CDF-experiment: 2D distribution of H_T vs M_{rec} distribution showing the data (black points) and the fitted number of background events; QCD (purple circles), W+JETS (green squares) and $t'\bar{t}'$ (blue triangles)

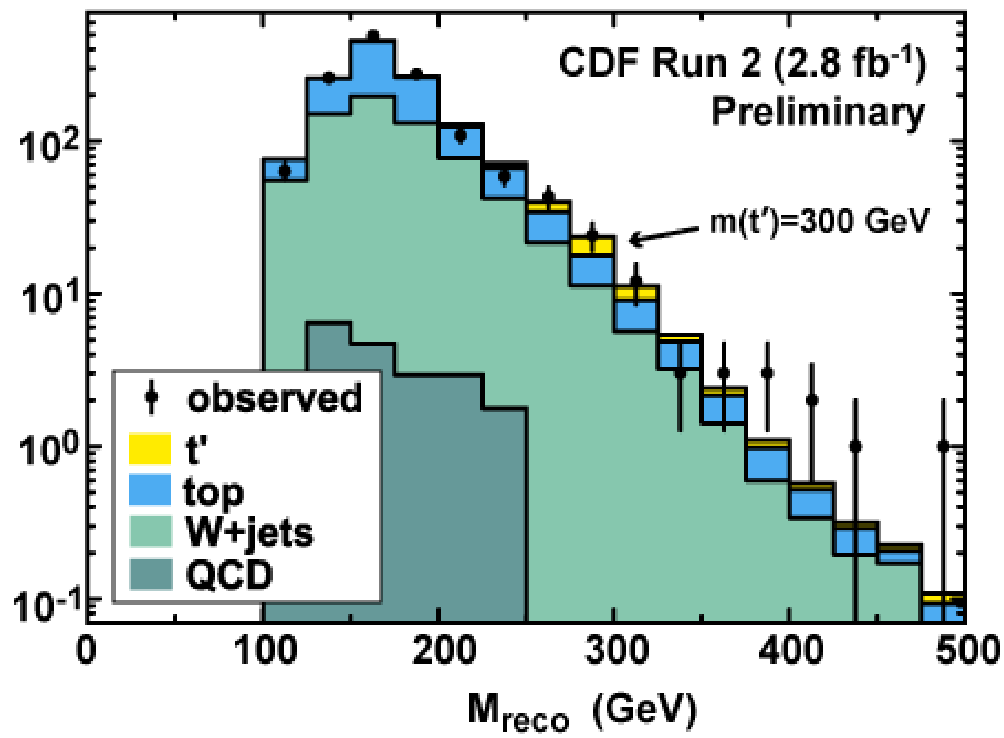

Fig. 18: Tevatron CDF-experiment: observed and predicted distribution of M_{reco}. The predicted distribution corresponds to that for a 300 GeV/c^2 mass t' signal with a cross-section times branching ratio at the 95% CL upper limit.

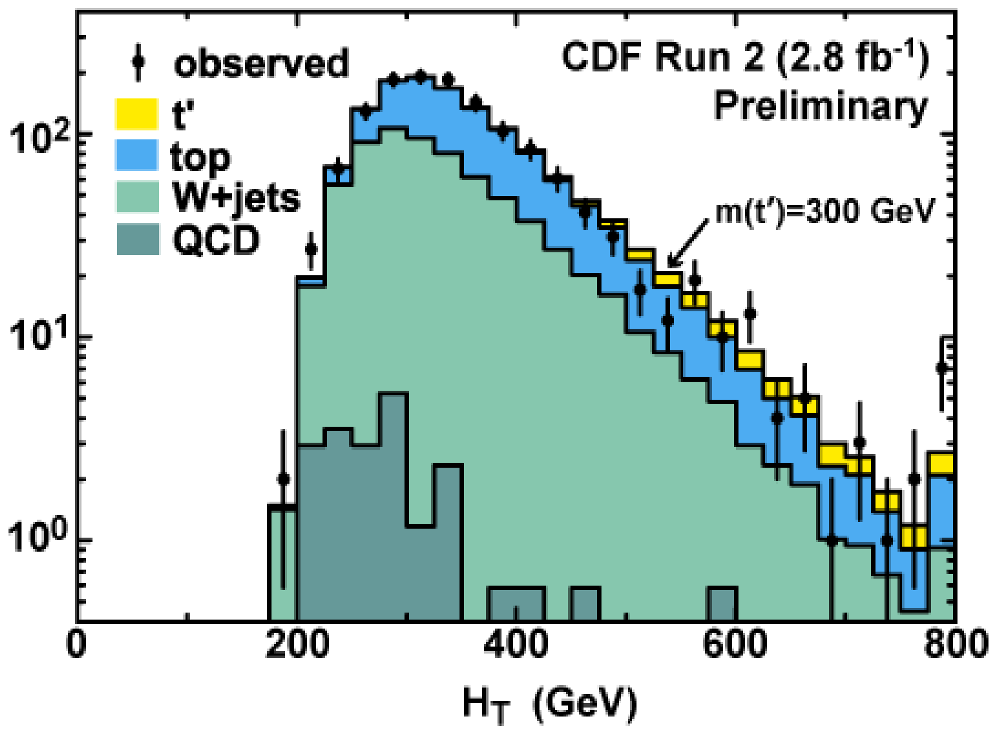

Fig. 19: Tevatron CDF-experiment: observed and predicted distribution of H_T.

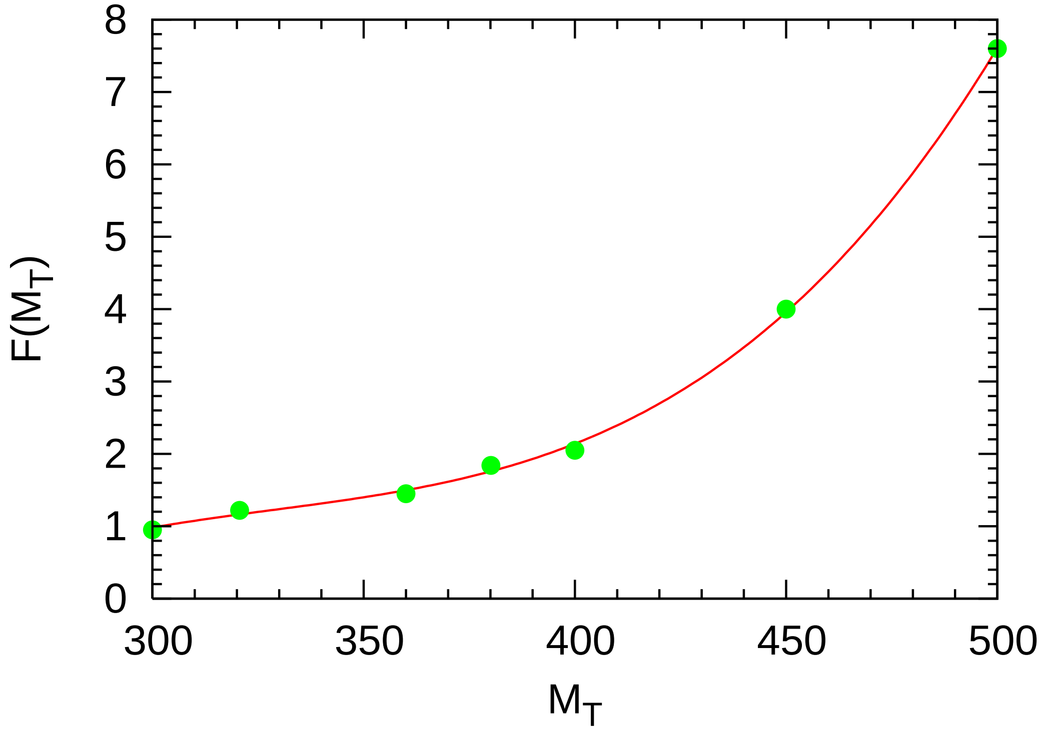

Fig. 20: The fermionic NBS T_f form-factor $F(M_T)$ from Tevatron CDF-experiment in absence of the four-generation quarks

11 Estimate of the NBS form-factors in the Tevatron CDF-experiment

Assuming that there a fourth family of t'-quarks does not exist in Nature, but only the fermionic NBSs T_f with mass $M_T > 300$ GeV are produced at the Tevatron (see Fig. 14) in the CDF-experiment [26, 27], given by Fig. 15, we can imagine the existence of form-factors of the NBS T_f in the cross-section of their production:

$$\sigma(p\bar{p} \to T_f\overline{T_f}) = F^2(M_T)\sigma_{theor}(M_T), \tag{45}$$

where M_T is the T_f-mass. Here $\sigma(p\bar{p} \to T_f\overline{T_f})$ is given by observed red line curve of Fig. 15 and $\sigma_{theor}(M_T)$ is the theoretical (blue) curve (see Bonciani et al., Refs. [28, 29] for the point-like particle t'; see also [30]). The numerical calculations give the result shown in Fig. 20 in the region of M_T from 311 GeV (where $F(M_T) = 1$) up to 500 GeV. We conclude that for $M_T = 500$ GeV the form-factor is large enough:

$$F(M_T) \approx 7.6. \tag{46}$$

12 Charge multiplicity in decays of T-balls

Actually Li and Nielsen suggested in Ref. [11] that the NBSs would decay to a rather low number of jets, but at first one might very reasonably think that since we have to do with bound states of very many constituents and actually $6t\bar{t}$ pairs, it sounds that the possibility of them decaying into as many jets as there are pairs to annihilate, say - or even the number of constituents - has some intuitive appeal and should not just be thrown away as a possibility by the Li-Nielsen rather non-safe argument. We shall therefore here develop what we would expect in the case of the separate $t\bar{t}$ pairs decaying essentially separately, although we do not really believe that any longer: if the mass of the NBS, containing 6 pairs of $t\bar{t}$, is M_S, then the energy per one annihilation of $t\bar{t}$ approximately is equal to the following value:

$$E_{an} = E_{(for\ one\ annihilation)} \approx \frac{1}{6}M_S, \tag{47}$$

e.g.

$$E_{(for\ one\ annihilation)} \approx 10\ GeV,$$

if

$$M_S \approx 60\ \text{GeV}.$$

In this case, during the annihilation produced by e^+e^--collisions, the special charge multiplicity is

$$< N_{NBS,\,ch}(e^+e^-) >\approx 10,$$

while the annihilation produced by pp-collisions, the special charge multiplicity is

$$< N_{NBS,\,ch}(pp) >\approx 6.$$

Such calculations of $< N_{NBS,\,ch} >$ vs E_{an} are based on the investigation of Ref. [31]. Here for $M_S \approx 60\ GeV$ we obtain the following values for the charge multiplicity:

$$N_{NBS,\,ch}(e^+e^-) \approx 6 \cdot 10 \approx 60, \tag{48}$$

$$N_{NBS,\,ch}(pp) \approx 6 \cdot 6 \approx 36. \tag{49}$$

The value of the charge multiplicity weakly depends on the NBS mass. For instance, if $M_S \approx 80\ GeV$, then:

$$< N_{NBS,\,ch}(pp) >\approx 6.5,$$

and

$$N_{NBS,\,ch}(pp) \approx 6 \cdot 6.5 \approx 39. \tag{50}$$

But if $M_S \approx 100\ GeV$, then:

$$< N_{NBS,\,ch}(pp) >\approx 7,$$

and

$$N_{NBS,\,ch}(pp) \approx 6 \cdot 7 \approx 42. \qquad (51)$$

However, such a maximally possible charge multiplicity will not be realized in practice, because between the produced in the final state pairs $t\bar{t}$, or $b\bar{b}$, can exist extra exchanges by gluons and the Higgs bosons giving new annihilations. And we shall obtain less jets.

Since it may be pretty unlikely that all six $t\bar{t}$ pairs should annihilate just simultaneously, while that is what they have to do for the whole T-ball to decay, we expect the decay rate of the T-ball to rather suppressed compared to the rate for more forwardly decaying particles of otherwise similar properties. Thus it would indeed be very strange if the decay width of the T-ball is not small. Indeed we expect the width of the T-ball to be small. Then we would have narrow peaks in JETS. It would be exactly a good way to see that our model is right if we could find some narrow peak in the distribution of the total mass of some JETS.

For pp-collisions the estimates [11] give :

$$\frac{dN_{NBS,\,ch}}{d\eta}|_{max} \approx 6. \qquad (52)$$

Such a value is expected for this derivative at LHC (see Fig. 21). The maximum of this curve corresponds to the LHC energy $w = \sqrt{s} = 14$ TeV in pp-collisions.

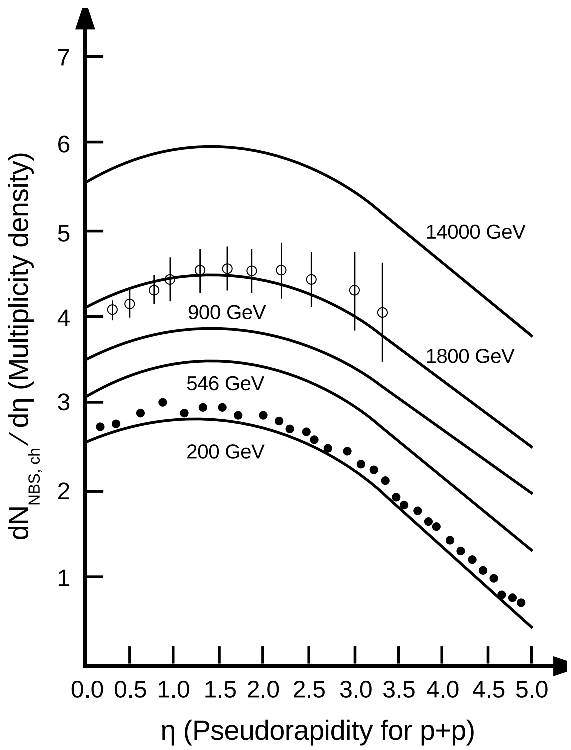

Fig. 21: The prediction of the possible density of charge multiplicity $\frac{dN_{NBS,\,ch}}{d\eta}$ in pp collisions at LHC (η is a pseudorapidity for $p+p$).

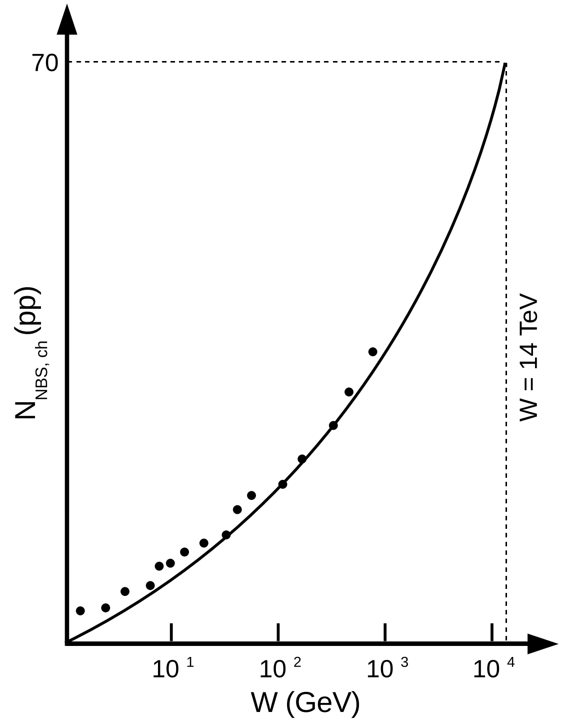

Fig. 22: The prediction of charge multiplicity in pp collisions at LHC.

The dependence $N_{NBS,\,ch}$ vs w is presented in Fig. 22. Here

$$N_{NBS,\,ch}(pp)|_{w=14\ TeV} \approx 70. \tag{53}$$

These calculations (figures) show that T-balls can give an essential contributions to charge multiplicity in pp-collisions, provided that their decays really go as if each $t\bar{t}$ pair decayed separately and not as the recent estimate by Li and Nielsen [11].

13 Conclusions

1. The present investigation devoted to the main problems of the Standard Model is based on the following three assumptions: 1) there exists $1S$–bound state of $6t+6\bar{t}$, e.g. bound state of 6 quarks of the third generation with their 6 anti-quarks; 2) the forces which bind these top-quarks are so strong that they almost completely compensate the mass of the 12 top-quarks forming this bound state; 3) such strong forces are produced by the Higgs interactions: the interactions of top-quarks via the virtual exchange of the scalar Higgs bosons coupling with a large value of the top-quark Yukawa coupling constant g_t.

   A new bound state $6t+6\bar{t}$, which is a color singlet, was first suggested by Froggatt and Nielsen and now is named 'T-ball'.

2. Present theory also predicts the existence of a new bound state $6t + 5\bar{t}$, which is a color triplet and a fermion similar to the quark of the fourth generation.

3. We have also considered "b-replaced" NBSs: $T_S(n_b b-\text{replaced}) = n_b b + (6t + 6\bar{t} - n_b t)$ and $T_f(n_b b - \text{replaced}) = n_b b + (6t + 5\bar{t} - n_b t)$, where n_b is the integer number. The presence of b-quarks in the NBS leads to the dominance of the isospin singlets: with the inclusion of both b and t quarks we obtain a picture, that is more invariant under weak isospin.

4. We have estimated the masses of the lightest "b-replaced" NBSs: $M_{T(b-\text{replaced})} \simeq (300 - 400)$ GeV, and predicted the existence of the more heavy "b-replaced" NBSs: $M_{T(n_b b-\text{replaced})} > 400$ GeV with $n_b > 1$.

5. We have developed a theory of T-ball's condensate, and predicted the possibility of the existence of three SM phases at the EW-scale. Calculating the top-quark Yukawa coupling constant at the border of two phases (with T-ball's condensate and without it) we have obtained $g_t \approx 1$.

6. It was shown that CDF II Detector experiment searching for heavy top-like quarks at the Tevatron (in $p\bar{p}$-collisions with $\sqrt{s} \backsimeq 1.96$ GeV) can observe T_f-balls with masses up to 500 GeV.

7. We have considered all processes with T-balls, which can be observed at LHC, especially the decay
$$H \to 2T_s$$
and the production of
$$T_f\overline{T_f}$$
as an analog on the $t'\overline{t'}$ production (where t' is the quark of the fourth generation with t-quark quantum numbers).

8. We have estimated the charge multiplicity at the energy w=14 TeV at LHC:
$$N_{NBS,\,ch}(pp)|_{w=14\ \text{TeV}} \approx 70,$$
and have shown that the charge multiplicity coming from the T-ball's decays is of order of this value provided we make the hypothesis of essentially independently decaying t-anti t pairs and assume multiplicities like other production mechanisms.

9. In this investigation we have argued that T-balls can explain why it is difficult to observe the Higgs boson H at colliders: T-balls can strongly enlarge the decay width of the Higgs particle.

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